

The influence of calcite loading on producer gas composition and tar concentration of radiata pine pellets in a dual fluidised bed steam gasifier

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HIGHLIGHTS

- ▶ H_2/CO can be varied from 0.9 to 4.2 by increasing calcite loading and S/B at 100% calcite loading.
- ▶ Change in calcite loading provides flexibility to meet required H_2/CO in target applications.
- ▶ Total tar concentration decreased exponentially from 5.0 to 0.7 g/Nm³ with the calcite loading.
- ▶ Tar reduction from 0% to 50% calcite loading was found to be higher than that from 50% to 100% loading.

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ABSTRACT

This study has investigated the influence of calcite loading on the producer gas composition and the tar concentrations on a 100 kW_{th} dual fluidised bed (DFB) steam gasifier. In the experiments, wood pellets of radiata pine were used as the feedstock and the operating temperature in the bubbling fluidised bed reactor (BFB) was set at 710–750 °C while that in the fast fluidised bed reactor (FFB) was controlled at 800 °C. In the first part of the experiments, the calcite loading was varied at 0%, 50% and 100% at constant steam to biomass (S/B) ratio of 0.8 kg/kg_{dry}. In the second part of the experiment, the influence of S/B ratio was examined at 50% and 100% calcite loadings. The present study has concluded that the ratio of H_2/CO can be varied from 0.9 to 4.2 by increasing the calcite loading and the S/B ratio only at 100% calcite loading. In addition, the total tar concentration decreased exponentially from 5.0 to 0.7 g/Nm³ with the calcite loading. This method provides the flexibility to meet the required H_2/CO in target downstream applications. However, the disadvantage of increasing calcite loading was that the attrition rate increased exponentially from 0.5% at 0% loading to 4.1 kg/h at 100% loading. The tar reduction from 0% to 50% calcite loading was found to be higher than that from 50% to 100% calcite loading. This could be mainly due to the suppressing effect of high partial pressure of H_2 on the steam reforming of those tar compounds.

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1. Introduction

Biomass is a sustainable source for generation of low carbon energy and liquid fuels [1–3] and it is expected to play a critical role in the future. New Zealand has a huge potential for growing biomass crops due to the suitable climate conditions and arable land which has not been fully used [4]. In addition, residues generated from forest harvesting, wood processing and agricultural industries contributed approximately 6.5% (mainly for steam generation) of the total primary energy supply in 2009 [4].

Biomass conversion is the key for promoting biomass energy and bio-liquid fuels. Biomass gasification has recently attracted increasing attention due to the advantages of high conversion efficiency and flexibility in using the producer gas as the gasification product. The producer gas, which consists of combustible gases including H_2 , CO, CH_4 and other light hydrocarbons, can be used for steam generation, electricity production or can be converted to liquid fuel through Fischer–Tropsch (FT) synthesis process. However, contaminants in the producer gas such as tars, ammonia (NH_3), hydrogen sulphide (H_2S), hydrogen chloride (HCl) and particulates are required to be removed prior to any downstream application. In order to produce clean producer gas with high hydrogen content and high calorific value, a 100 kW_{th} dual fluidised bed (DFB) steam gasifier has been constructed and extensive experiments have been conducted by this research team at the University of Canterbury, New Zealand [5–10].

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In reported studies, most of the existing fluidised bed gasifiers were operated at temperatures above 800 °C and using expensive metal based catalysts as bed material in order to achieve high gas yield with low tar concentrations [11–24]. Such high gasification temperatures can cause bed agglomeration or sintering when low ash melting point fuel of agro-residues are used as the feed-stock [25]. Although high temperature biomass gasification tends to reduce tars concentration in the producer gas, the tars contain higher proportion of Class 4 and 5 poly-aromatic hydrocarbons (PAHs), which have higher boiling points, and thus have greater impact on the gas quality compared to the low temperature gasification which produces relatively simple tar compounds in the producer gas [13,24,26,27]. Note that the classification of tar compounds is based on the study by Kiel et al. [28]. Low temperature gasification also tends to have high cold gas efficiency (CGE) due to less heat demand and less heat loss for a gasifier plant [26]. Therefore, a low cost catalytic bed material can be used at the operating temperature less than 750 °C if required.

Among the reported catalysts for biomass gasification bed material, calcite (CaO based material) is an inexpensive, abundant and naturally occurring non-toxic catalyst that has the catalytic activity for tar reduction [29–31]. Several studies have been demonstrated that calcite is an excellent CO₂ removal sorbent from combustion flue gases and the reaction for this effect is shown in Eq. (1) [32–34]. In the steam biomass gasification, calcite is also established to be a promising bed material to enhance H₂ production due to the in situ reactions of CO₂ absorption and water–gas shift, Eq. (2), with the optimum operating temperature of around 700 °C, which process can be described by Eqs. (1) and (2) [31,35–45]. Details of the in situ reactions are well described in the review article by Florin and Harris [46]. In previous studies on the DFB biomass gasification with calcite as the bed material, H₂ content of the producer gas as high as 50–75% (mol) has been reported with corresponding CO content of 6–17% (mol) and tar concentration of 1–2 g/Nm³ [39,41,42,47]. In these studies, 100% of calcite was used to achieve the high H₂/CO ratio of three or higher, which is in excess of the optimum value of two for FT synthesis. In addition, the calcite as a bed material in the fluidised bed gasifier has high attrition rate, resulting in high bed material loss [47–51]. The bed material attrition is induced by surface wear and impact damage [52]. Therefore, there is a potential to reduce the calcite loading to achieve the optimum H₂/CO ratio for the FT synthesis, and thus reducing the calcite attrition rate. To date, no study has been reported on the effect of the calcite loading on the producer gas composition and tar content in the steam biomass gasification.



Recent studies by Acharya et al. [44] and Han et al. [45] have demonstrated that increasing of steam to biomass (S/B) or steam to carbon (S/C) ratio was favourable to increase the H₂ content and the gas yield in a bubbling fluidised bed reactor (BFB) in the presence of CaO. The increase of the H₂ content was due to the promotion of carbonation activity of CaO (Eq. (1)) by increasing the S/C. This, in turn, enhanced the forward direction in the water–gas shift reaction (Eq. (2)) [45]. However, no study has been reported on the effect of S/B on the producer gas composition and tar content in a DFB gasifier. The aims of the present study are, therefore, to investigate (i) the influence of the calcite loading on the producer gas composition and the tar concentration; (ii) the influence of S/B ratio on the producer gas composition and the tar concentration at various calcite loadings; and (iii) the influence of the calcite loading on the attrition rate.

2. Experiments and materials

2.1. Experiment setup

Fig. 1 is the schematic diagram of the 100 kW_{th} dual fluidised bed (DFB) steam gasifier for the present study. The gasifier consists of a bubbling fluidised bed (BFB) gasification reactor with steam as fluidisation agent and a fast fluidised bed (FFB) combustion reactor fluidised with air. The BFB has an internal diameter of 0.2 m with a height of 2 m and the FFB has an internal diameter of 0.1 m with a height of 3.7 m. The biomass was fed via a screw auger from the wood pellet hopper into the bubbling bed layer of the BFB, approximately 0.13 m above the reactor base. In order to prevent the undesired back flow of the producer gas from the feeder, approximately 5 L/min of N₂ was introduced into the hopper. In the experiments, the biomass char and the bed material at the base of the BFB were transferred hydraulically through the inclined chute to the FFB. In the FFB, the char was combusted along with supplementary liquefied petroleum gas (LPG) to regenerate the calcite based bed material from CaCO₃ to CaO at a temperature around 825 °C (calcination). The primary combustion air was supplied at the base of the FFB and was also used to fluidise the solid material for it to be in good contact with the secondary combustion air, which was introduced 200 mm above the primary air nozzles. The bed material was fluidised upwards and was carried out of the FFB into the FFB cyclone, which separated the heated bed material from the combustion flue gas. The bed material was then delivered back to the BFB through the siphon to provide heat for the biomass gasification. Both the chute and the siphon were

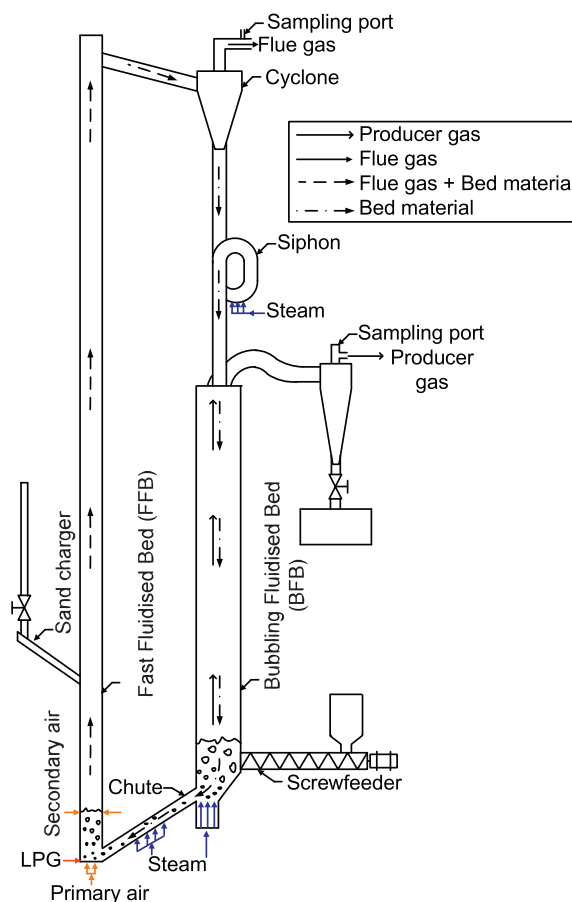


Fig. 1. Schematic of the operation of the University of Canterbury dual fluidised bed steam gasifier.

fluidised with controlled steam to prevent cross-flows of gases between the FFB and the BFB, and to maintain high solid circulation rate. The producer gas generated carried out of the BFB and the entrained fine particles of char, ash and bed materials were separated from the producer gas in the BFB cyclone. The fine particles were then collected in the trap collector, which could be emptied during the gasifier operation if needed. At the same time, equal amount of fresh bed material was introduced into the gasifier system through the sand charger located at the FFB (Fig. 1) to compensate the lost bed material during the experiment. Samplings of the producer gas were conducted at the sampling port located after the BFB cyclone. In the current study, the producer gas was incinerated in an afterburner.

2.2. Materials and operation conditions

In the present study, wood pellets of *Pinus radiata* (radiata pine), which chemical compositions are given in Table 1, were used as the fuel source for the gasification experiments. Three different compositions of the bed materials were tested, which were (i) 0% calcite (100% greywacke), (ii) 50% calcite (50% calcite in greywacke) and (iii) 100% calcite. The chemical analysis results of both the greywacke and the calcite bed materials are presented in Table 2. The physical characteristics of the bed materials and the operation conditions are given in Table 3. In the first part of the experiments, the S/B ratio was set at 0.8 and the gasification temperatures were controlled at 710–750 °C. The total bed materials loading was 18 kg while the feeding rate of the wood pellets was set at 13.8 kg_{dry}/h. In the second part of the experiments, the S/B was varied from 0.67 to 0.95 (kg/kg_{dry}) for the calcite loading of 50% and 100%, while the other operation parameters remained the same as in the first part. In the experiments, a small quantity of steam at flow rate of 2 kg/h was injected into both the chute and the siphon to enhance the bed material flow. The bed materials loading in this study was increased to 18 kg from the previous study of 12 kg based on the finding that the CGE and gas quality were improved with increase in the bed material loading [9].

2.3. Producer gas and tar sampling and analysis

During the gasification runs, the producer gas samples were extracted through a 3 mL Supelclean LC-NH₂ solid phase extraction (SPE) column, which trapped the tar components in the producer gas for further tar sample extraction. The first 50 mL aliquot was extracted from the sampling line using a plastic sample collection syringe and then expelled. This process was to flush out the air trapped in the syringe. The second 50 mL aliquot was extracted in the same way and stored in the sample syringe, which was then sealed, removed from the sampling system and transported to an Agilent 3000 micro-gas chromatography-thermal conductivity

detector (GC–TCD) for gas analysis. The micro-GC consists of two columns, which were a 10 m × 0.32 mm MolSieve 5A Plot operated at 110 °C and an 8 m × 0.32 mm Plot Q operated at 60 °C. The MolSieve 5A Plot column was used to separate H₂, N₂, CH₄ and CO while the Plot Q column was used to separate CO₂, C₂H₄ and C₂H₆.

The tar extraction method in the present study was adopted from the study of Brage et al. [53]. The tar in each SPE column was eluted with a 1 mL of dichloromethane (DCM) and was spiked with a 100 mg/L of *n*-dodecane as an internal standard (IS) into a 2 mL vial to obtain aromatic and PAH components. The same SPE column was then eluted again with a 1 mL mixture of DCM and isopropanol, IPA (1:1 v/v) and was spiked with a 100 mg/L of the IS into another 2 mL vial to obtain phenolic fractions.

For the tar analysis, a Varian CP-3800 GC with a flame ionisation detector (GC–FID) was used in which the tar samples were separated in a 50% phenyl and 50% dimethylpolysiloxane fused silica capillary column of 30 m × 0.25 mm × 0.25 µm with Varian VF-17 ms. The temperature of the injector and the FID was set at 300 °C. Each tar sample of 1 µL was injected into the injector with an autosampler. To provide a good separation of the analytes, the column temperature was programmed with the column conditions controlled at: (i) 50 °C hold for 1 min, (ii) from 50 to 180 °C at a rate of 4 °C/min, (iii) from 180 to 245 °C at a rate of 2.5 °C/min, (iv) from 245 to 270 °C at a rate of 2 °C/min and hold for 10 min and (v) from 270 to 350 °C at a rate of 8 °C/min and then hold for 5 min. The flow rate of the carrier gas, helium, was set at 1 mL/min.

Prior to the tar analysis, an IS calibration was conducted with the same column conditions as described above to obtain the response factor for each tar standard relative to the IS of 100 mg/L. Note that the tar standards adopted in the present study are shown in Table 4 and the tar classification system proposed by Kiel et al. [28] was followed. Five different concentrations were prepared and analysed and each concentration was measured three times.

3. Results and discussion

3.1. Influence of calcite loading on the producer gas composition

The influence of calcite loading on the composition of producer gas free of N₂ is shown in Fig. 2 for biomass gasification with S/B of 0.8. With the increase in calcite loading, the H₂ content in the producer gas increased from 29% to 58% whereas the CO content decreased from 32% to 15% and that of CO₂ from 23% to 15%. In addition, the CH₄ content decreased slightly from 12% to 10% whereas the other light hydrocarbons (LHs) content decreased from 5% to 2%, respectively, with the increase of calcite loading. The increase in H₂ content in the producer gas can be explained by the in situ CO₂ absorption by the CaO as shown in Eq. (1), which enhanced the forward direction in the water gas-shift reaction, Eq. (2) [41,42,46,54]. In Eq. (1), the forward reaction or the carbonation reaction is an exothermic reaction, and thus the reduced temperature in the BFB reactor favoured the forward the CO₂ absorption. Salvador et al. [55] has reported that the recycling of carbonation may reduce the reactivity of the calcite bed material due to the surface layer sintering for increased resistance for heat and mass transfer. However, in the present study, the bed materials were circulated, which would inhibit the formation of the surface resistance layer. In addition, fresh bed materials at the same composition as originally loaded were added during the experimental run to compensate the lost bed material.

In the steam biomass gasification, the reactions of steam reforming of CH₄ (Eq. (3)) and gaseous hydrocarbons (Eq. (4)) were also observed as the concentrations of CH₄ and LH were slightly decreased. The slight influence of the calcite loading is due to the

Table 1

The lower heating value (LHV) and chemical compositions of wood pellets in the present study.

Proximate (%)	Method	
Total moisture	ISO 5068	8.0
Volatile matter	ISO 562	77.4
Fixed carbon	By difference	14.2
Ash	ASTM D1102	0.4
Ultimate (%)		
Carbon	Microanalytical	51.3
Hydrogen	Microanalytical	5.81
Nitrogen	Microanalytical	<0.2
Sulphur	ASTM D4239	<0.1
Oxygen	By difference	42.6
LHV (MJ/kg)	ISO 1928	18.6

Table 2
XRF analysis result of the major elements (wt.%) present in the greywacke and calcite sand. Note that Loss on Ignition (LOI) represents the volatile components such as hydrated water, carbonate and carbon present in those sands.

	SiO ₂	Al ₂ O ₃	Na ₂ O	Fe ₂ O ₃	K ₂ O	CaO	MgO	P ₂ O ₅	MnO	TiO ₂	LOI
Greywacke	76.33	11.35	3.30	2.61	2.06	1.25	0.71	0.08	0.04	0.55	1.49
Calcite	0.36	<0.2	<0.1	0.09	0.05	54.88	0.51	0.02	0.02	0.01	43.82

Table 3
The operating conditions of the present study on the gasifier.

	0% calcite loading	50% calcite loading	100% calcite loading
Average BFB temperature (°C)	730–750	710–720	710–730
Average particle size of the sand (μm)	250	380	400
Bulk particle density, ρ_b (kg/m ³)	1600	1400	1500
Steam to biomass ratio (kg/kg _{dry})		0.67–0.95	
Biomass feed rate (kg _{dry} /h)		13.8	
Total amount of bed material in the gasifier (kg)		18	
Average FFB temperature (°C)		825	

Table 4
The classification of tar compounds detected in the present study according to Kiel et al. [28].

ECN Class	Tar compound
2 (heterocyclic)	Phenol, o/m-cresols
3 (aromatic)	Toluene, xylene, styrene
4 (light poly-aromatic hydrocarbons)	Biphenyl, 1 and 2-methylnaphthalene, naphthalene, acenaphthylene, acenaphthalene, fluorene, phenanthrene, anthracene,
5 (heavy poly-aromatic hydrocarbons)	Fluoranthene, pyrene, benz(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(k)fluoranthene, benzo(a)pyrene, indeno(1,2,3-cd)pyrene, benzo(g,h,i)perylene, dibenzo(a,b)anthracene

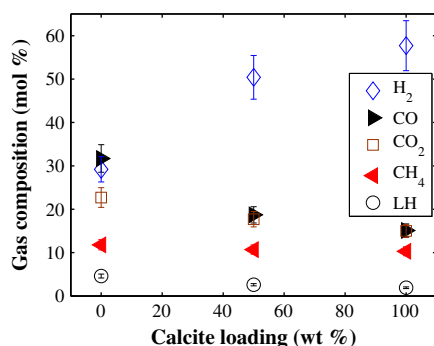
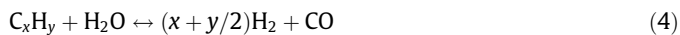


Fig. 2. The influence of calcite loading on the dry producer gas composition from steam biomass gasification (S/B = 0.8). Note that LH represents light hydrocarbons.

increase in H₂ content, which, to a certain extent, counters the forward reactions. Similar finding has been reported by Hu and Huang [43] and Han et al. [45].



The results shown in Fig. 2 are re-organised as gas ratios of H₂/CO, H₂/CO₂ and CO/CO₂ (mol/mol) and the results are illustrated in Fig. 3. It was found that the H₂/CO ratio increased from 0.9 to 3.8 with the calcite loading increasing from 0% to 100% while the corresponding values of H₂/CO₂ ratio increased from 1.3 to 3.8. However, the ratio of CO/CO₂ was found to decrease from 1.4 to 1.0. The change in the ratios can be explained by the absorption of CO₂ that is dependent on the amount of CaO in the system. In the meantime, CO is consumed through water–gas shift reaction (Eq. (2)), which is the dominant reaction between 730 and 830 °C [24]. From the results, the H₂/CO ratio can be linearly correlated to the calcite

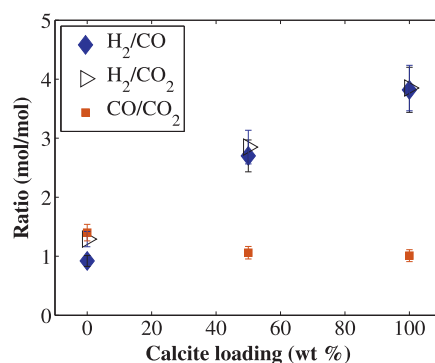


Fig. 3. The influence of calcite loading on the ratios of H₂/CO, H₂/CO₂, CO/CO₂ in the producer gas from steam biomass gasification (S/B = 0.8).

loading. Based on this correlation, the optimum H₂/CO ratio of two for FT synthesis of liquid fuel can be achieved at the calcite loading of 35%.

3.2. Influence of calcite loading on the tar compounds

The influence of calcite loading on each class of tar is shown in Fig. 4 in which the concentrations of C₂, C₃ and C₄ tars are read from the left hand y-axis and C₅ tar concentration from the right hand y-axis. The concentration of the C₂ tar compounds was significantly reduced by 91%, as the calcite loading was increased from 0% to 50%, and was then further reduced by 44% with the increase of calcite loading from 50% to 100%. The concentration of the C₃ tar compounds was reduced by 70% at 50% calcite loading and was further reduced by 25% as the calcite loading was increased to 100%. Similar to the C₂ tar compounds, the concentration of the C₄ tar compounds was reduced by 80% at 50% calcite loading and was further reduced by 25% from 50% to 100% calcite loading. For the C₅

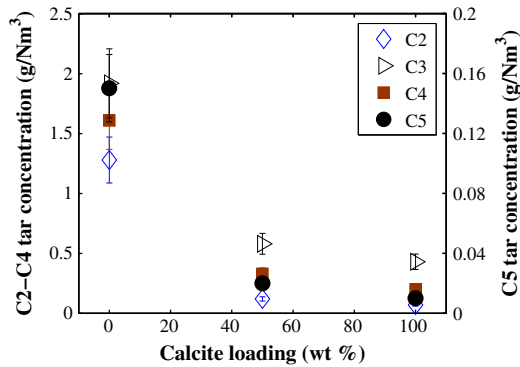


Fig. 4. The influence of calcite loading on concentrations of each class of tar in the producer gas from steam biomass gasification (S/B = 0.8).

tar compounds, the concentration was reduced by 85% at 50% calcite loading and further reduced by 56% at 100% calcite loading. It has been reported that the tar formation is a very complex process and many parallel reactions can be taken place during the gasification, however, the tar reduction with the calcite loading was most likely due to the steam reforming of tars in the presence of CaO [40]. The difference in the degree of tar reduction from 0% to 50% calcite loading compared with that from 50% to 100% calcite loading could be due to the suppressing effect of H_2 on the steam reforming of those tar compounds [56–59]. The negative effect of high partial pressure of H_2 in the present study can be explained by the results from studies conducted on calcined dolomite (CaO, MgO), where the decrease in the decomposition rate of tar compounds, such as benzene, phenol, toluene and naphthalene was due to the dissociation of H_2 and absorbed onto the active sites of the CaO and MgO ($Ca^{2+}-O^{2-}$ and $Mg^{2+}-O^{2-}$) [58,60,61]. Overall, the total tar concentration (sum of all the tar compounds) decreased exponentially from 5.0 to 0.7 g/Nm³ with the calcite loading from 0% to 100%.

3.2.1. C2 tar compounds

In addition to the overall tar concentration in the producer gas, the concentration of individual species of tar compounds in each class were also analysed in the present study. Fig. 5 presents the influence of calcite loading on each species of the C2 tar compounds. Phenol was identified to be the major C2 tar compound followed by m- and o-cresols. The reduction of C2 tar compounds in the producer gas was mainly due to the catalytic effect of calcite on the steam reforming of phenol and cresols as shown in Eqs. (5) and (6) [58,62,63]. The concentration of phenol decreased by 93% and that of both cresols by 96% as the calcite loading was increased from 0% to 100%:

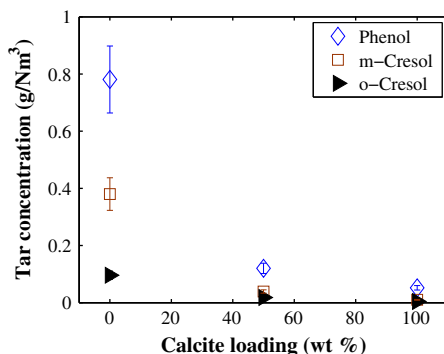
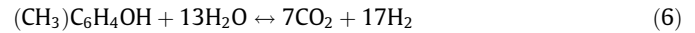


Fig. 5. The influence of calcite loading on each species of C2 tar compounds in the producer gas from steam biomass gasification (S/B = 0.8).



3.2.2. C3 tar compounds

The influence of calcite loading on C3 tar compounds is shown in Fig. 6. Toluene was identified to be the major species of the C3 tar compounds followed by styrene and xylene. As expected, the influence of calcite on the steam reforming of C3 tar compounds was not as significant as the highly reactive of C2 tar compounds. The concentration of the C3 species was decreased by 70% for toluene, 74% for styrene and 89% for xylene, as the calcite loading was increased from 0% to 100%. The complexity of steam reforming of toluene can be simplified, which produces either H_2 and CO or H_2 and CO_2 , as shown in Eqs. (7) and (8), respectively [64–66]. Although the C3 tar concentration for all the conditions was high, its influence on the tar dew point is insignificant:



3.2.3. C4 tar compounds

Fig. 7 presents the influence of calcite loading on the C4 tar compounds. It is found from the present study that naphthalene was the major C4 tar compound, which agrees with the findings in the previous studies [28,31,67]. With the increase in activity of steam reforming of tar, the concentration of naphthalene was significantly reduced by 73% from 0% to 50% calcite loading and addition reduction of 31% was observed with the calcite loading was increased from 50% to 100%. Similar tar reduction was observed for the rest of C4 tar compounds including 1- and 2-methylnaphthalene as well as acenaphthylene.

It is interesting to find from the present study that although the overall concentration of tar compounds were significantly reduced with the calcite loading, the fraction of naphthalene in the C4 tar compounds increased from 32% to 49% as the calcite loading was increased from 0% to 100%. The increase of the proportion of naphthalene could be due to the inhibition of the naphthalene-steam reaction by the increase of H_2 content in the producer gas with the calcite loading [56]. In addition, the increase of naphthalene could be due to the cracking of larger PAH components, which naphthalene was produced as the major byproduct.

3.2.4. C5 tar compounds

Fig. 8 presents the influence of calcite loading on the concentrations of each species of C5 tar compounds. The C5 tars are the most important as they have the highest tar dew point at

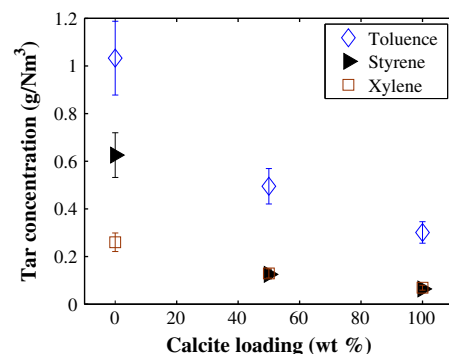


Fig. 6. The influence of calcite loading on each species of C3 tar compounds in the producer gas from steam biomass gasification (S/B = 0.8).

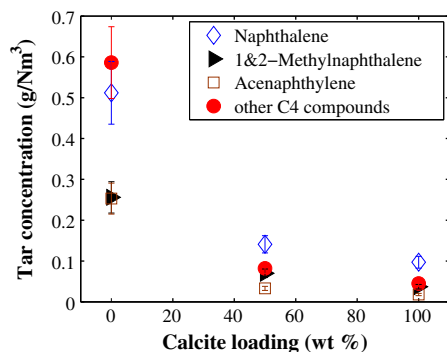


Fig. 7. The influence of calcite loading on each species of C4 tar compounds in the producer gas from steam biomass gasification ($S/B = 0.8$).

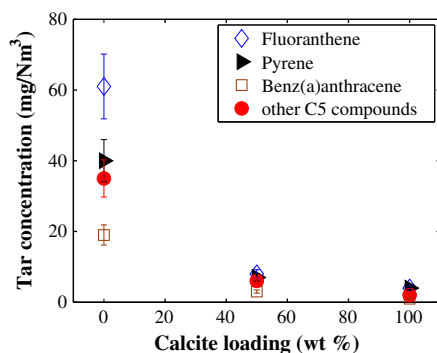


Fig. 8. The influence of calcite loading on each species of C5 tar compounds in the producer gas from steam biomass gasification ($S/B = 0.8$).

low concentration, and thus will condense first while the producer gas cools down. In the C5 tars, fluoranthene was found to be the major compound followed by pyrene, benz(a)anthracene and the remaining compounds. In a similar trend to other class tars, the concentration of each heavy C5 tar compounds were also decreased with the calcite loading. At present, the information of C5 tar compounds activity is limited due to the complex molecular structure of the heavy compounds, however, it is believed that the steam reforming activity as shown in other tar classes contributed to the reduction in the C5 tar compounds. Further studies are needed to give a more precise analysis.

3.3. Influence of S/B ratio on the producer gas composition

3.3.1. For 50% calcite loading

Figs. 9 and 10 present the influence of S/B ratio varies from 0.67 to 0.96 ($\text{kg/kg}_{\text{dry}}$), respectively, on the producer gas composition and tar compounds at 50% calcite loading. It is found that there was no influence of S/B ratio on the producer gas composition (Fig. 9) and the tar compounds (Fig. 10) with the S/B ratio. The insignificant influence of steam on the tar reduction agreed with the results obtained from the studies on the tar models [57,68].

3.3.2. For 100% calcite loading

The experimental results on the influence of S/B ratio at 100% calcite loading are shown in Fig. 11 for the producer gas composition. The concentrations of tar compounds in the producer gas is shown in Fig. 12. From Fig. 11, it is observed that the H_2 concentration was increased from 57% to 62% whereas CO concentration was decreased from 17% to 15% and that of CO_2 was reduced from 13% to 11% with the S/B ratio increase from 0.67 to 0.96. The gas concentration changes with the S/B ratio resulted from the promotion

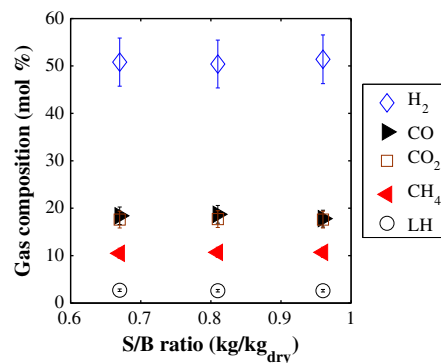


Fig. 9. The influence of S/B ratio on producer gas composition in steam biomass gasification at 50% calcite loading. Note that LH represents light hydrocarbons.

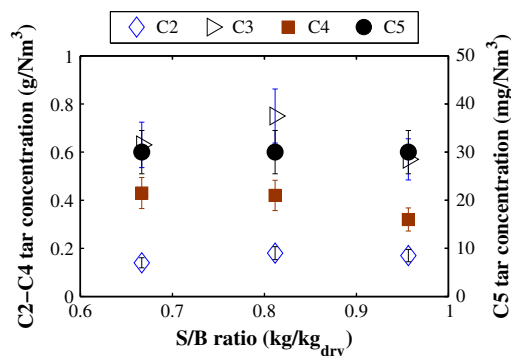


Fig. 10. The influence of S/B ratio on the concentrations of tar compounds in the producer gas from steam biomass gasification at 50% calcite loading.

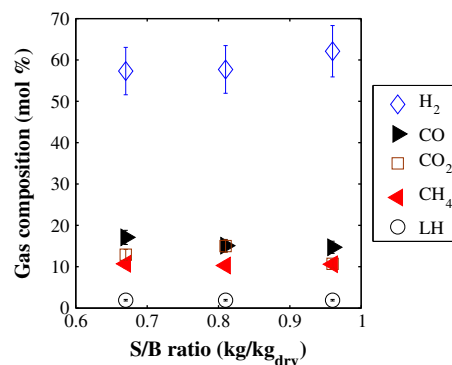


Fig. 11. The influence of S/B ratio on the producer gas composition and cold gas efficiency (CGE) in steam biomass gasification at 100% calcite loading. Note that LH represents light hydrocarbons.

of CaO reactivity on the in situ reactions of (1) and (2) as described earlier. Similar observations of the gas composition changes were reported in the previous studies [43–45]. Consequently, the ratio of H_2/CO increased from 3.4 to 4.2 with the increase in the S/B ratio from 0.67 to 0.95.

At 100% calcite loading, the S/B ratio had more influence on the tar compounds compared with the 50% calcite loading. The concentration of the C5 tar compounds decreased significantly from 40 to 8 mg/Nm^3 while the concentration of the C3 tar compounds (toluene and xylene) slightly increased from 0.4 to 0.6 g/Nm^3 with increase in the S/B ratio. However, the concentrations of C2 and C4 tar compounds (mainly phenol and naphthalene, respectively) were almost unchanged with the S/B ratio. The decrease in C5

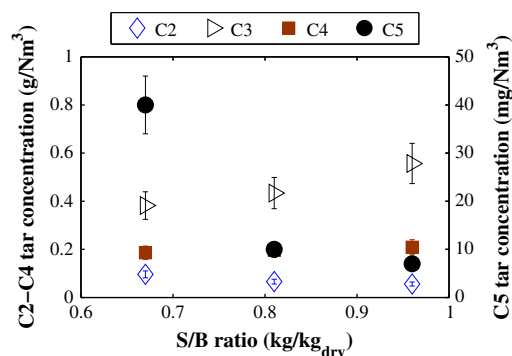


Fig. 12. The influence of S/B ratio on the concentrations of tar compounds in the producer gas from steam biomass gasification at 100% calcite loading.

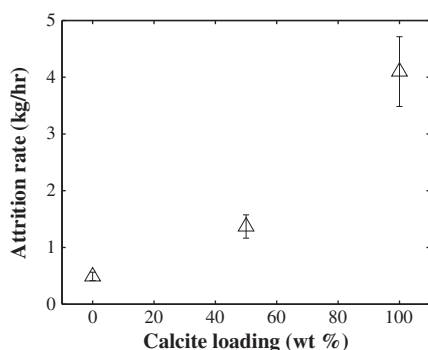


Fig. 13. The attrition rate as a function of the calcite loading in the steam biomass gasification.

compounds and the increase in C3 compounds could be associated with increase in H_2 resulting from the promotion of carbonation activity of CaO by the increase in S/B ratio. Further studies are needed to provide better understanding on such complex reactions.

3.4. Attrition rate

Fig. 13 presents the attrition rate as a function of the calcite loading in the steam biomass gasification experiments at the S/B ratio of 0.8. As expected, the attrition rate increased exponentially from 0.5 to 4.1 kg/h with the calcite loading from 0% to 100% due to wear action and impact damage of the low mechanical strength of the calcite. In addition, the formation of $Ca(OH)_2$ under steam environment will further aggravate the calcite attrition [45]. The attrition rate was calculated based on the total amount of fine particles entrained by gases both from the FFB and the BFB per unit time of gasifier operation in the experiment. Such attrition rate may be relatively low in the pilot scale gasifier but the attrition rate in a demonstration plant and a commercial scale gasification plant can induce significant costs for the lost bed materials although the calcite dust can be used as the ingredient for construction materials [69–71].

4. Conclusion

In this study, the influence of calcite loading on the producer gas composition and the tar concentration was experimentally investigated on a 100 kW_{th} dual fluidised bed (DFB) steam gasifier using radiata pine pellets as the feedstock. The effect of steam to biomass (S/B) ratio was also investigated on the producer gas

composition; however, the effect was found to be significant only at 100% calcite loading. The detailed tar species of each tar class (C2–C5) was analysed and gives good understanding of the tar decomposition with the calcite. The present study has concluded that the ratio of H_2/CO can be varied from 0.9 to 4.2 by increasing the calcite loading and changing the S/B ratio at 100% calcite loading. This method provides the flexibility to meet the required H_2/CO in target downstream applications. However, the disadvantage of increasing calcite loading was that the attrition rate increased exponentially from 0.5 kg/h at 0% loading to 4.1 kg/h to 100% loading.

The tar reduction from 0% to 50% calcite loading was found to be higher than that from 50% to 100% calcite loading. This could be due to the suppressing effect of high partial pressure of H_2 on the steam reforming of those tar compounds. Overall, the total tar concentration decreased significantly from 5.0 to 0.7 g/Nm³ with the calcite loading increase from 0% to 100%. The most significant improvement with the calcite loading is the reduction of C5 tar compounds in the producer gas as they have the highest tar dew point.

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